CHAPTER 5

Summary

5.1 Conclusions and perspectives

Since the time of Newton the study of celestial objects had enormous impact on the theoretical physics. It is the observations of planetary objects moving around the Sun which stimulated and for certain extent verified the Newtonian mechanics. Motion of the celestial objects e.g. comets in the solar system continued to attract great minds of post-Newtonian era like Lagrange. It was again the 'N body' problem inspired from solar system, which resulted in Henri Poincare's monumental work on chaotic orbits. In that sense the entire dynamical system theory is grateful to astronomy. Again Lynden-Bell's violent relaxation opened a new frontier in statistical mechanics with applications stretching from galactic dynamics to laser technology. Whether it is the classical dynamics of point objects, the helium spectra from Sun, the existence of degenerate fermionic gas (with an exception of metallic conduction), nuclear fusion, the extreme case of spacetime singularity, all of them got their initiation and encouragement form astrophysics.

The story of astrophysical accretion disk is different. The accretion disk research is in such a privileged state that more than becoming a contributor to the general physics it is clearly taking advantage of the refined and much studied frontiers of advanced physics and technology. One of the principal issues with the accretion disk is the turbulent viscosity and its origin, which in fact is not entirely an astrophysical problem. The problem of turbulence is being studied since much before fluid dynamics found any reasonable application in astrophysics. It is again the genius of astrophysicist which allowed the community to bypass the issue of turbulent viscosity in the study of the accretion flow, in the form of α viscosity (explained in Chapter 1 and applied in Chapters 3, 4). The question is, whether it is enough for an astrophysicist to rely on the already existing theories and methods of instability and turbulence. The answer is 'no'. In fact MRI (briefly explained in Chapter 1) is having an altogether astrophysics origin and a great contribution to the field of MHD instability. Miserable failure by fluid dynamics community in completing the theory of hydrodynamic instability in certain shear flows never discourages astrophysicists to get involved with that. The case of variabilities of radiation from accretion disk systems is also not entirely different. Although entirely out of scope of the present work, we would like to mention that under close proximity these variabilities and underlying disk dynamics fit well within the advanced theories of dynamical systems. The present work can be by and large divided into two parts: the study of hydrodynamic instability mechanism and global solution of transport equations. Both the topics are at the heart of the accretion flow research and continue to evolve rapidly.

The main results of Chapter 2 can be summarized as follows.

- We have analysed the linear hydrodynamic stability of local rotating accretion disk patch for various angular velocity distributions.

- We have included the approximate first order non-linear correction to the stability analysis and an amplitude equation is setup.

- We find that at sufficiently large Reynolds number the flow is conditionally unstable against perturbation.

- We find that the Coriolis force and epicyclic frequency have nontrivial influence in the finite amplitude perturbation analysis.

- We are able to obtain a lower limit of energy input which will make the accretion disk locally unstable.

In the case hydrodynamic stability analysis of a local rotating accretion disk patch we have demonstrated that weak non-linearity could route the perturbation to an unstable state. Although this by itself is something of great importance to demonstrate, by no means finishes the stability analysis as a whole. One of the most difficult parts of hydrodynamic instability of accretion disk is to pinpoint an energy limit which is relevant in distorting the laminar flow. We believe that this goal is attained, at least partially if not complete. The importance given to various angular velocity distribution is quite justified since almost all flows in the astrophysical domain possess angular velocity of some kind. Even for a Keplerian flow local non-Keplerian nature is argued by several authors. Given the fact that we have demonstrated the non-linear instability, the question of turbulence remains quite an open problem in the case of accretion disk. If one proceeds in a systematic manner, it is experienced that the channeling of energy from the base flow to the non-linearly unstable mode is a very delicate process, which is yet to be demonstrated. This requires a large amount of work and an almost parallel walk along with the researchers in general fluid mechanics community. We hope to move with this aim in mind for our future explorations.

The main results of Chapter 3 can be summarized as follows.

- The sub-Keplerian two temperature accretion disk around a rotating black hole is modeled with bremsstrahlung as cooling mechanism.

- The flow properties are studied in a wide range of 'α' in the cases of static and rotating black holes.

• With the help of the model we could reproduce the observed luminosity of Sgr A*.

• With the help of the model we argue that Sgr A* is an intermediate/low spinning black hole with Kerr parameter $\lesssim 0.5$.

• With the help of the model we are able to obtain luminosity of ULX sources.

• The model predicts that the accretion disk around ULX sources have high viscosity.

The main results of Chapter 4 can be summarized as follows.

• The sub-Keplerian two temperature accretion disk is modeled self-consistently without any presumptions of flow variables (which to our knowledge is first of this kind).

• The stability of the flow against convection is checked explicitly.

• The model naturally explains all phases of the sub-Keplerian accretion flow such as general advective accretion flow (GAAF), ADAF (proposed previously by others) and the transition from one phase to the other.

• The model incorporates all the major non-thermal cooling mechanisms.

• The model is able to explain the under-luminous to the ultra-luminous sources (e.g. Sgr A*, PKS0743-67, SS433), stellar mass to supermassive black holes.

In Chapters 3, 4 we have studied the global solutions of a sub-Keplerian accretion disk around rotating black holes. The entity black hole comes into picture mainly in two ways: the pseudo-Newtonian gravitational potential which mimics the Kerr geometry in the equatorial plane and the inner boundary condition in the conservation equations. We have tried to incorporate the available information such as various cooling processes to obtain self-consistent global solutions. Our main objectives were to study the influence of spin of the black hole on the disk properties, the self-consistent and natural transition of accretion among different phases such as radiatively inefficient flow and general advective accretion flow and then to reproduce the observed luminosity of certain objects with reasonably good observational information. We had free parameter α with other genuine free parameters such as mass of the black hole and mass accretion rate. Mass and the mass accretion rate can have a wide range of value and if they are to be fixed by other methods (e.g. mass of the black hole can be fixed by the orbital period of a luminous object revolving around it such as binary companion) we see that there is a crucial interplay between spin of the black hole and viscosity of the accretion disk. Spin of the black hole is a fundamental property and the viscosity (α) of the accreting matter is a phenomenological property. Both can affect the global solution strongly and a judicious choice is advocated to explain a particular system. The physics involved in accretion disk systems is so diverse and numerous that to include every aspect is rather cumbersome and not of much use always. Because of that the modeling of accretion disk should have certain objectives (as we pointed out earlier). We have avoided some of those effects in formulating our equations such as coronal heating of emitted photons, neutrino cooling, nuclear burning etc.

The first major success in accretion disk modeling came as the standard Keplerian α-disk model, where α is a geometric parametrization of the complex dynamics of fluid turbulence. Immediately after that people started thinking how to generalise the same. The standard Keplerian model was written within the framework of general relativity. Later on the idea of sub-Keplerian component of the accretion disk was proposed. Efforts were made to self-consistently include jet-outflow with in the equations for disk. In all these efforts the α prescription remained central. But this arises certain conceptual difficulties. Is the α prescription something unique? Will this α prescription survive mounting evidence of diversity among numerous accretion disk systems found observationally? Is it really sensible to describe the thermal spectra as well as non-thermal peaks with the same expression for turbulent energy dissipation? If all these suspicions are of no practical consequence, can we rigorously justify α prescription once and for all? It is for sure that one can only make opinion and a consensus seems impossible.

Surprisingly the efforts to go to much more general framework of a turbulent accretion flow are few in number. As we already mentioned there is nothing as such 'fundamentally astrophysical' in formulating transport phenomena of turbulent accretion disk. Methods and tools are available. One of such work, we particularly like to mention, is Dubrulle 1992 (in the language of Dubrulle (1992) " ...it is now well documented [methods applied in the paper]..."). The Reynolds stress which we commonly use in describing the turbulent transport is only a zeroth order expression and more general closure models are available. Interestingly enough in engineering and geophysics these closure models are applied with great success. We have tried to demonstrate shear driven instability in Chapter 2 and in Dubrulle (1992) the closure model explicitly assumes this to be the case. The motivation of such modeling need not be only the numerical fixing of α (which of course can be done) but obtaining the general structure of the turbulent accretion disk. What makes the modeling of transport in accretion disk more distinct from other fields of similar nature such as engineering and geophysics is that altogether new features and complications arise in the case of accretion disk. For example the mechanism of turbulence could be due to shear instability, convection driven instability or MRI. Extra effects such as stratification, compressibility and sometimes self-gravity enter into the picture. Thus many nontrivial generalizations are required in the case of closure models for accretion disk.

Thus we understand that whether it is the hydrodynamic instability mechanism, closure models and global solutions, disk oscillations the theory and modeling of astrophysical accretion disk has a long way to cover hand in hand with the observationalists in the field.